COMBINED STEAM TURBINE - GAS TURBINE SUPERCHARGED CYCLES EMPLOYING COAL GASIFICATION

E. A. Pirsh

The Babcock & Wilcox Company, Barberton, Ohio

W. L. Sage

The Babcock & Wilcox R&D Division, Alliance, Ohio

Introduction

Over the years, various cycles have been proposed for combining a gas turbine plant with a steam turbine plant. The major advantages advanced for such cycles were the improvement in overall cycle efficiency and the reduction in capital costs.

There are a number of combined plants in commercial operation but none are of the supercharged type and marginal economic advantages have limited general acceptance. Further, none employ coal as the single fuel.

Preliminary studies indicated that there were combined cycles which offered a better economic advantage than those then in use. Further, certain cycles appeared capable of circumventing most of the problems which had precluded the use of coal as the single fuel in existing combined plants.

In view of the tremendous potential of an attractive cycle, a program was initiated which had as its objective the development of a coal-fired, combined steam turbine-gas turbine electric generating plant with a 5 per cent lower heat rate and a 5 per cent lower capital cost than a comparable size, modern, conventional steam electric plant.

Conclusions

Sufficient development work was conducted to establish that there was an arrangement of a supercharged combined cycle which was technically feasible provided that alkali levels up to 5 ppm could be tolerated by the gas turbine.

However, during the course of the project, several important economic factors significantly affected achievement of the project's objective...

1. Coal prices decreased in many areas, thus diminishing the value of heat rate improvement.

2. Capital costs of conventional plants decreased very significantly. Thus, the potential for reducing costs below those for conventional plants was adversely affected.

Because of these factors, the economic objectives of the project could not be achieved. Consequently, further work was deferred until such time that the influencing factors changed sufficiently to alter the economic evaluation. Today, air pollution control introduces considerations which may alter the previous economic evaluation and cycles which have the potential for effective and economical air pollution control are being considered for development.

Discussion

Engineering studies had been made during a period of several years prior to initiation of this project in order to select the optimum cycle for development. Those studies concluded that a supercharged boiler cycle would afford the maximum potential for meeting the cycle efficiency and capital cost objectives. Also a specific design of gas-turbine was selected on the basis of its performance capabilities and operational compatability for integration in a large (450 MW) steam plant. This turbine was a General Electric Frame Size 8 with gas inlet conditions of approximately 1600F and 95 psia and driving a compressor delivering about 440 pounds of air per second. Two such turbines would be integrated in a 450 MW combined plant.

The usual concept of a supercharged boiler cycle in which the gas is cleaned between the boiler and the gas turbine is shown in Figure 1. In this cycle, coal is fired into a supercharged boiler where the combustion conditions, aside from the high pressure, are similar to those in a conventional boiler. All of the steam generation, superheating, and reheating is accomplished in the supercharged boiler. The hot gases from the supercharged boiler are cleaned and admitted to the gas turbine. From the viewpoint of gas turbine erosion, the gas can be cleaned adequately in a series of high efficiency mechanical collectors. However, this degree of cleaning is not sufficient to prevent gas turbine corrosion and deposits in a high temperature gas turbine. Some improvement in gas cleaning can be gained through the use of an electrostatic precipitator. However, an electrostatic precipitator will not remove volatile ash constituents which can cause deposition and corrosion.

Since cleaning of high temperature combustion gases did not appear feasible, and it did not appear possible to design a turbine intolerant to the problems of erosion, corrosion and deposition, the cycle shown in Figure 2 was considered to be more promising and was selected as the basis for development. In this cycle, all of the coal is gasified to produce a fuel gas with a heating value of about 100 BTU/SCF. The gas leaves the producer at about 900F and is cleaned with a combination of mechanical and electrostatic cleaners. The gas is then fired in a combustor, cooled to 1600F by passage over the superheater and reheater surface and is admitted to the gas turbine. The exhaust gases from the gas turbine are cooled by passage over air heater and economizer surface. Under typical conditions, feedwater is introduced into the gas producer at about 580F and leaves as steam at about 780F. The steam then flows to the combustor where it is superheated and reheated. An obvious advantage of this cycle is that the gas clean-up is performed at 900F instead of 1600F. Further, less than one-half of the gas to the turbine requires cleaning and the size of the clean-up apparatus is therefore reduced as compared to the supercharged boiler cycle. Since clean gas is fired to the combustor, the possible problems of corrosion and fouling of the superheaters and reheaters are reduced in severity.

The main problems recognized at the time that development work was outlined were those of...

1. Deriving a coal gasification process suitable for application to a power plant.

2. Corrosion in the reducing environment of the gas producer.

3. Developing a system capable of adequately cleaning the make-gas from the producer.

Initial laboratory test work on coal gasification consisted of the exploration of two gasification processes. These are shown in Figure 3. The first of these was a fixed-bed process in which coal was fired, with theoretical air, in a lower furnace. The hot gases passed upwards and countercurrently to a coal bed, several feet thick, and fed from above. The coal bed was supported on a water-cooled tubular grate and was operated with the lower portion slagging.

The second gasification process was a suspension system which also utilized a lower furnace in which fuel was fired with theoretical air. The hot combustion gases passed upwards and crushed coal of the sizing of 1/4 inch x 0 was injected into these gases at the outlet of the primary furnace. The gas velocities were maintained sufficiently high to keep the coal in suspension. This gasifier was constructed with an annular space between a silicon carbide tube, in which gasification took place, and an outer jacket. Combustion gases from a natural gas burner at the top flowed through the annulus to reduce heat losses from the gasification zone.

The experimental results obtained from the operation of these two gasifiers revealed that the fixed-bed process provided a somewhat richer gas than that obtained from the suspension process. However, the fixed-bed process produced tars which were considered troublesome whereas the gas from the suspension process was tar-free. The processes also were evaluated on the basis of their suitability to large power plant application and from the standpoint of adaptability to a wider range of coal properties and coal sizing and considerations of design, construction and operation, the suspension process was selected as the better choice.

The next step in gas producer development consisted of the design and construction of a large suspension gasifier with a coal gasification rating of about 5000 pounds per hour. This gasifier went into operation on June 1961 and an isometric view of the apparatus is shown in Figure 4.

The main components of this apparatus were the gasifier in which the make-gas was produced and the combustor, in which the make-gas was burned. Air from the forced draft fan passed through the primary section of the air heater and a portion was supplied as combustion air to the combustor. The remaining portion passed through the secondary section of the air heater and was supplied to the gasifier at temperatures up to 1000F. The coal was pulverized in an air swept mill and conveyed with primary air to the burners. The gas produced was cooled over convection heat absorbing surface to about 800F and entered two 42 inch cyclone collectors where the coarse fly-coke was removed from the gas. The fly-coke was collected in a hopper, fed through a rotary feeder and reinjected into the gasifier. The make-gas leaving the cyclone collectors was conducted to the combustor where it was burned with excess air.

This equipment was operated for about two years during which time a number of configurations of the gasifier were explored. The original arrangement consisted of a horizontal Cyclone Furnace firing into the gas producer shaft. All of the coal was injected into the base of the shaft and the fly-coke, which was separated from the make-gas, was refired into the Cyclone Furnace. Since the coal consumption in this gasifier was about 5000 pounds per hour, a single Cyclone Furnace was selected to avoid the combustion problems with multiple smaller-sized Cyclone Furnaces. However, the single Cyclone Furnace arrangement introduced gas flow distribution problems which would not exist to the same degree with multiple Cyclone Furnaces. Consequently, the final arrangement, Figure 5, with the horizontal Cyclone Furnace included a transition section between the Cyclone Furnace and the secondary furnace so constructed as to convert the gas spin on the horizontal axis into a gas swirl on the vertical axis.

Gas producer theory shows the very strong effect of gasification zone heat losses upon the heating value of the gas produced; and analysis of the horizontal Cyclone Furnace gasifier arrangement indicated that lower heat losses might be expected by using a vertical Cyclone Furnace firing upward into the gasification shaft.

At the same time, considerations based on theory and practice resulted in the recognition that the vertical Cyclone Furnace would have to operate at a lower rating than the horizontal Cyclone Furnace and that finer coal sizing would be required in order to prevent undue carbon loss to the slag. On the basis of these analytical studies and information obtained from plant visits and surveys of the operation and performance of modern European gas producers, it was decided to convert the horizontal Cyclone Furnace type producer to the vertical Cyclone Furnace type in order to explore the possible advantages of this arrangement and the configuration is shown in Figure 6.

The operation of this producer did not show any striking difference in performance. Both producers operated with acceptable carbon loss to the slag and the range of gas heating values obtained were comparable and of the order of 70-80 BTU/SCF. Extrapolation of these results to the lower percentage heat losses in a gasifier of commercial size predicted that gas with a heating value of 100 BTU/SCF could be expected from either type. The vertical Cyclone Furnace produced somewhat less lamp black but this, in itself, would not dictate the choice between the two. The choice involves consideration of other factors, foremost of which are the comparative costs and the producers, the associated fuel handling systems and the simplicity of operation. Summing up the results of the gas producer development work, two alternate types of gas producers were developed, either of which is applicable for use in a combined steam-gas turbine cycle of commercial size.

Investigations into the problem of corrosion in the reducing atmosphere of the gas producer consisted first of a literature search. Because of the difference in metal temperatures and partial pressures of the gas constituents, almost no previous gas producer corrosion experience could be found which applied under the conditions expected in a gas producer for a combined cycle. However, some petroleum refinery experience at the temperatures and hydrogen sulfide concentrations which were expected was available. The corrosion rates reported from carbon steel, the intermediate croloys, and even for the common austenitic stainless steels were discouraging. However, though the refinery experiences were at the hydrogen sulfide levels which were expected, the partial pressures of the other gas constituents were much different from the expected conditions. Experiments were therefore designed to test various alloys under conditions duplicating those expected in a commercial producer. The tests were conducted in autoclaves under the conditions of pressure, temperature, and gas composition expected in the commercial producer. These tests substantially confirmed the reported refinery experiences. Search for better alloys in subsequent tests ultimately led to two alloys which exhibited satisfactory corrosion resistance. The first of these was an 18 CR - 13 Ni steel with 2.5 per cent silicon. The second was an 18 CR steel with 4 per cent aluminum. These steels exhibited corrosion rates of about 0.003 inches per year at 950F metal temperature in the atmosphere expected in a gas producer fired with a 5 per cent sulfur coal.

The third major area in which development work was undertaken was the clean-up of the make-gas from the producer. The original concept for cleaning the make-gas to the degree required for the series gasifier and combustor cycle described earlier involved the combination of mechanical collectors followed by an electrostatic precipitator. It was recognized that the electrostatic precipitator involved the major difficulties expected. Therefore, an electrostatic precipitator was designed and built to investigate cleaning of the gas from the producer. Problems were immediately encountered in the way of insulator electrical shorting due to deposits of carbon black. This difficulty was largely overcome by employing a charged grid around the insulator together with gas sweeping using nitrogen as the purge gas. A small number of performance tests were conducted on the precipitator and the results indicated that the permissible gas velocities were so low as to make the precipitator for a commercial unit very large and prohibitively expensive.

It then was decided to determine whether the gas clean-up could be accomplished to a sufficient degree by mechanical means alone. Test apparatus was installed to determine the effectiveness of mechanical cleaning of the make-gas from the standpoint of turbine erosion. The apparatus, as shown in Figure 7, consisted of a series of mechanical collectors, a combustor where the producer gas was burned, a heat exchanger to cool the gas to the desired temperature entering the grids, a turbine grid simulating the first stage nozzles and blades and a steam ejector to produce the desired gas velocities through the grid. Test results indicated that the make-gas could be cleaned by mechanical means alone to the degree required to prevent gas turbine erosion.

However, it was recognized that cleaning of the make-gas by mechanical means only could introduce serious problems in the cycle originally selected for development. Two possible problems which were envisioned were...

1. turbine erosion due to ash agglomeration and subsequent spalling of coarse particles from the combustor convection surfaces and

2. corrosion in the gas turbine due to the build-up of alkali in the system.

The cycle, shown in Figure 8, was conceived to circumvent these difficulties. This cycle can be described as a parallel gas producer and supercharged boiler arrangement. In this cycle, the major portion of the coal is consumed in the supercharged boiler under normal conditions of excess air. The combustion gases are then cooled to 900F and cleaned in an electrostatic precipitator. Since the fly ash is free of carbon, the operation of this precipitator does not present the problems encountered when cleaning gas from the gasifier. In addition, the gas temperature is sufficiently low that volatile ash constituents are essentially absent and the alkali can be collected as a fume and discharged from the system. The operating temperature of the precipitator would not present difficulties due to electrical characteristics of the gas or ash.

Sufficient coal is gasified in the gas producer to supply the combustor with enough fuel to reheat all of the gas to the turbine to the desired inlet temperature. The gas turbine exhaust gases are cooled to the stack temperature with air heater and economizer surface in a manner similar to the series cycle.

Under typical conditions, feedwater enters the gasifier at 580F and leaves at 670F. It then passes to the supercharged boiler where the superheating and reheating takes place.

The parallel cycle possesses a number of important advantages over the series cycle. Perhaps the chief one is the simplification in the gas cleaning. In the case of the parallel cycle, alkali is rejected from the cycle along with the fly ash from the precipitator in addition to its disposal with the slag. The curves of Figure 9 show the relationship between the alkali concentration to the gas turbine and the make-gas cleaning efficiency for the parallel cycle with the assumptions indicated. The assumptions require a 95 per cent efficient mechanical collector to reduce the alkali to the turbine to 5 ppm when burning a 0.25 per cent total alkali coal. Further testing under gas turbine conditions of pressure and temperature would be required to assess whether an alkali level of 5 ppm in the gas to the turbine could be tolerated.

Since the gas producer requires stainless steel to provide corrosion resistance, it is a costly component in the cycle. In the parallel cycle, about 30 per cent of the coal must be gasified as compared with the need for 100 per cent gasification in the series cycle. The size and cost of this component, therefore, are reduced in the parallel cycle. This advantage is further augmented by the reduced temperature pick-up in the gasifier cooling circuit. The resulting lower metal temperature limits the corrosion rate to a tolerable level.

The parallel cycle presents further advantage in the way of the increased operating flexibility possible in the gasifier. Since the fly-coke removed from the make-gas is fired to the supercharged boiler, the gas producer need not operate under the condition of 100 per cent carbon utilization. This permits operation with a higher fuel to air ratio in the gasifier which produces gas with an increased heating value. In effect, the gas producer can be operated anywhere between the conditions of a gas producer or a carbonizer.

Evaluation of the considerable data obtained as a result of the research and development led to the assessment that a large scale plant, of the parallel cycle type, would be technically feasible provided that alkali levels up to 5 ppm could be tolerated by the gas turbine.

Engineering designs and studies closely paralleled the laboratory work throughout the entire development and analysis of the parallel cycle showed that the desired heat rate reduction could be obtained.

To determine whether the commercial development of this cycle could be justified, a 450 MW plant was designed to a sufficient degree that reliable cost estimates and evaluations could be made. Substantial engineering effort was expended in the design of all the plant components to assure functional and structural adequacy.

Sketches of the side elevation and the plan view of the plant arrangements which were developed are shown in Figures 10 and 11 respectively, and an artist's sketch of the plant is shown in Figure 12.

From these studies it was concluded that...

1. The machinery arrangement for a combined plant involves more components, is more complex and is inherently more expensive than that of a conventional plant.

2. A combined plant does not offer a substantial saving in the cost of plant components external to the boiler plant and steam generator.

3. The increased cost of the plant was greater than the value of the heat rate improvement.

4. The reductions made in the cost of conventional plants during the course of this development significantly affected the cost comparison between conventional and combined cycles.

5. The significant decrease in the average cost of coal delivered to utilities which occurred during the course of the project decreased the worth of heat rate improvement and was unfavorable to the combined cycle economic comparison.

A very thorough analysis of the economic and market evaluations concluded that the cycle did not offer sufficient economic inducement to justify the very large expenditure that would be required to continue the development to reach the commercial product stage. Accordingly, it was agreed that development should be discontinued until such time that major factors altered sufficiently to change the above conclusion.

The increasing emphasis on the control of air pollution has resulted in renewal of interest in combined cycles of the supercharged type which offer the potential for removal of the pollutants from gases at elevated pressures and of reduced volumes.

There are a number of cycles which have been proposed for this purpose and an example of one is shown in Figure 13. In this cycle, coal and air are fed to a pressurized, water-cooled gas producer which delivers combustible gas at about 900F. The particulate matter is then removed either mechanically or by filtering if filter media capable of operating at this temperature are developed. The sulfur compounds can be removed by solid adsorbents of the metal oxide type which can be regenerated to produce sulfur dioxide suitable for feed to a sulfuric acid plant. Alternately, regeneration to form elemental sulfur may be feasible and this is under investigation.

The clean combustible gas is fired in a combustor which discharges to a high temperature gas turbine which exhausts to the steam generating and heat recovery portion of the system. The water and the steam side of the cycle have been omitted from the figure for the sake of simplicity. Since the flame temperature in the combustor is less than that in a conventional coal-fired boiler furnace, significantly less nitrogen oxides will be produced.

Since the gas is produced and cleaned at high pressure, the size and possibly the cost of the gas producer and cleanup system would be significantly less than with atmospheric pressure systems. Further, the power cycle is more efficient and this, coupled with the value of sulfur recovered, indicates promise for an economical solution to the air pollution problem of the electric utilities.

Many of the important areas of this system have been developed through the pilot plant stage and the cycle is considered to be technologically feasible. However, the economic evaluation of the cycle and the development costs which would be required have not been examined in sufficient detail to permit conclusions concerning the commercial potential. Perhaps, with the application of sufficient engineering ingenuity, a cycle of this or a similar type may become the economical power plant of the future.

Acknowledgment

The development program which provided the basis for this paper was jointly sponsored by Babcock & Wilcox and General Electric. The efforts and technological contributions of the joint project team, consisting of members from both companies, are gratefully and respectfully acknowledged.

COMBINED STEAM-GAS TURBINE CYCLE WITH COAL-FIRED SUPERCHARGED BOILER

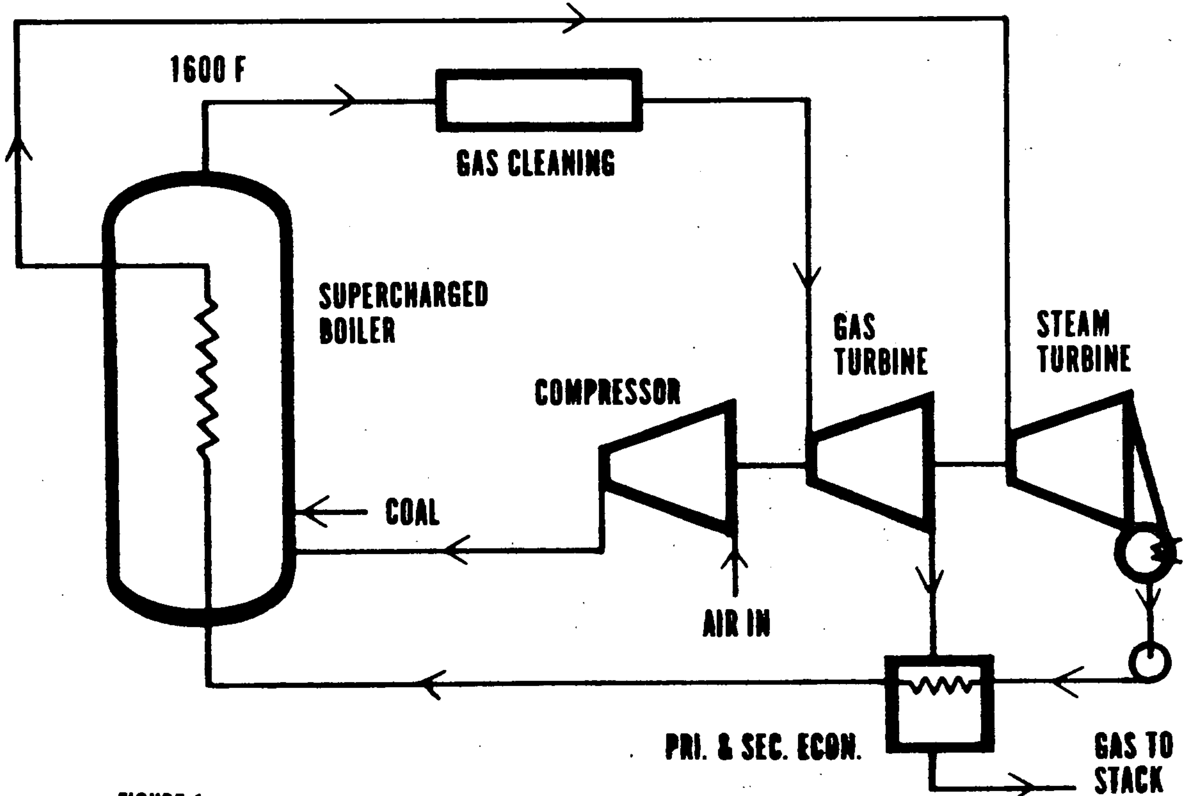


FIGURE 1

SUPERCHARGED GASIFIER COMBINED STEAM-GAS TURBINE CYCLE

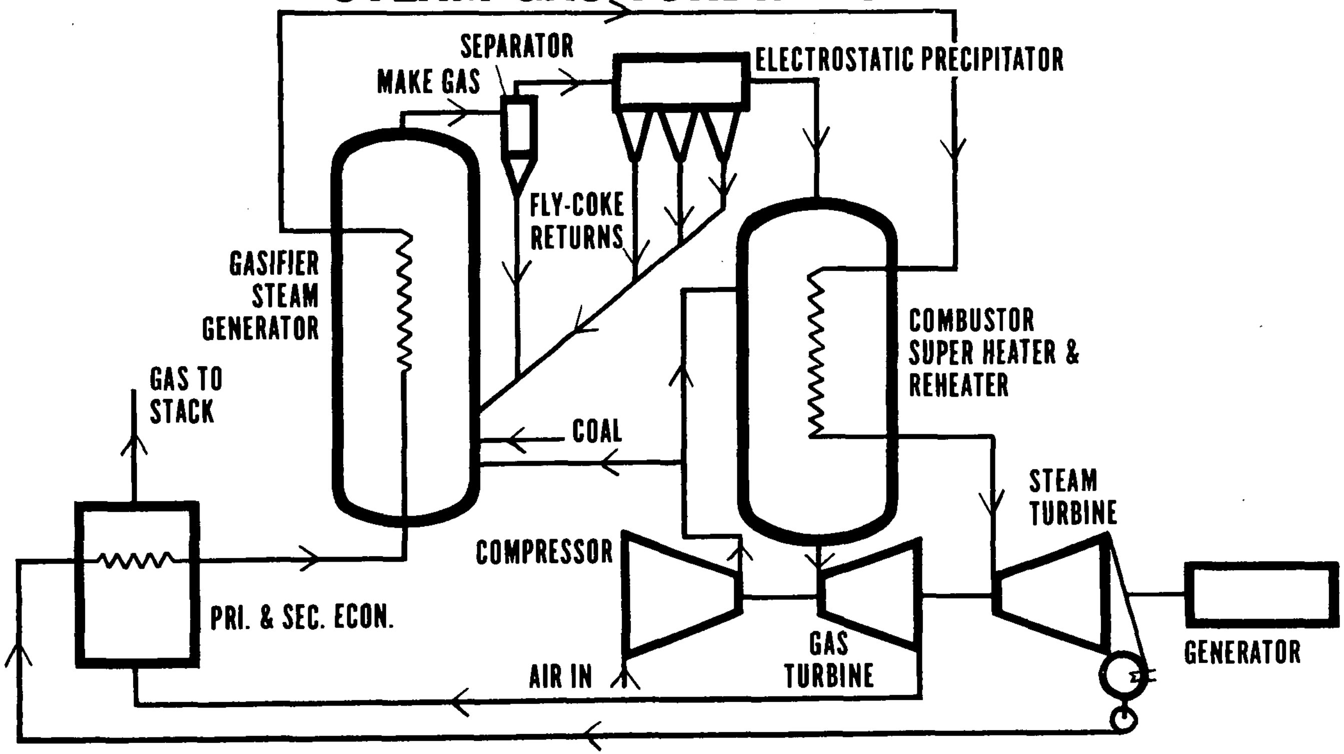
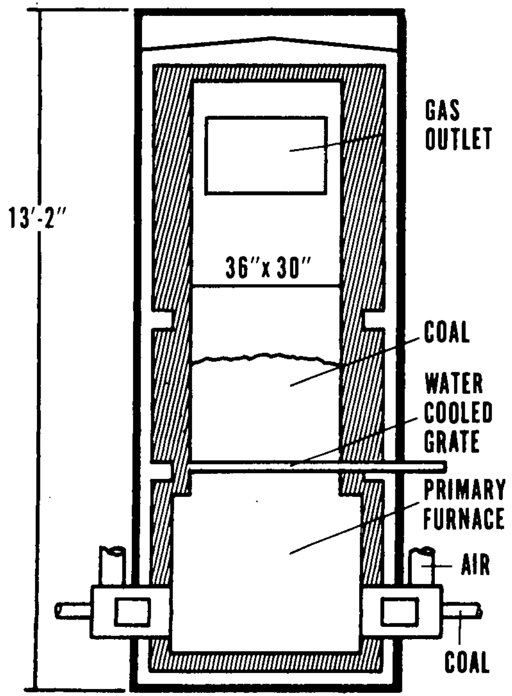


FIGURE 2

FIXED BED GASIFIER



SUSPENSION GASIFIER

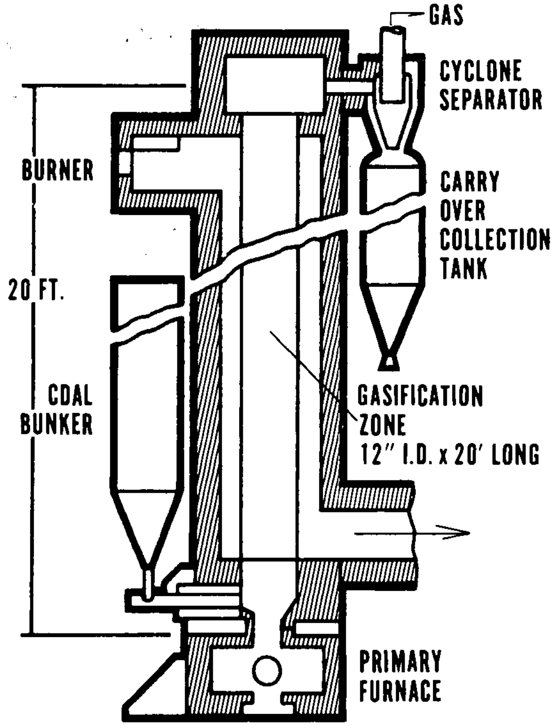


FIGURE 3

ALLIANCE LARGE SCALE GASIFIER

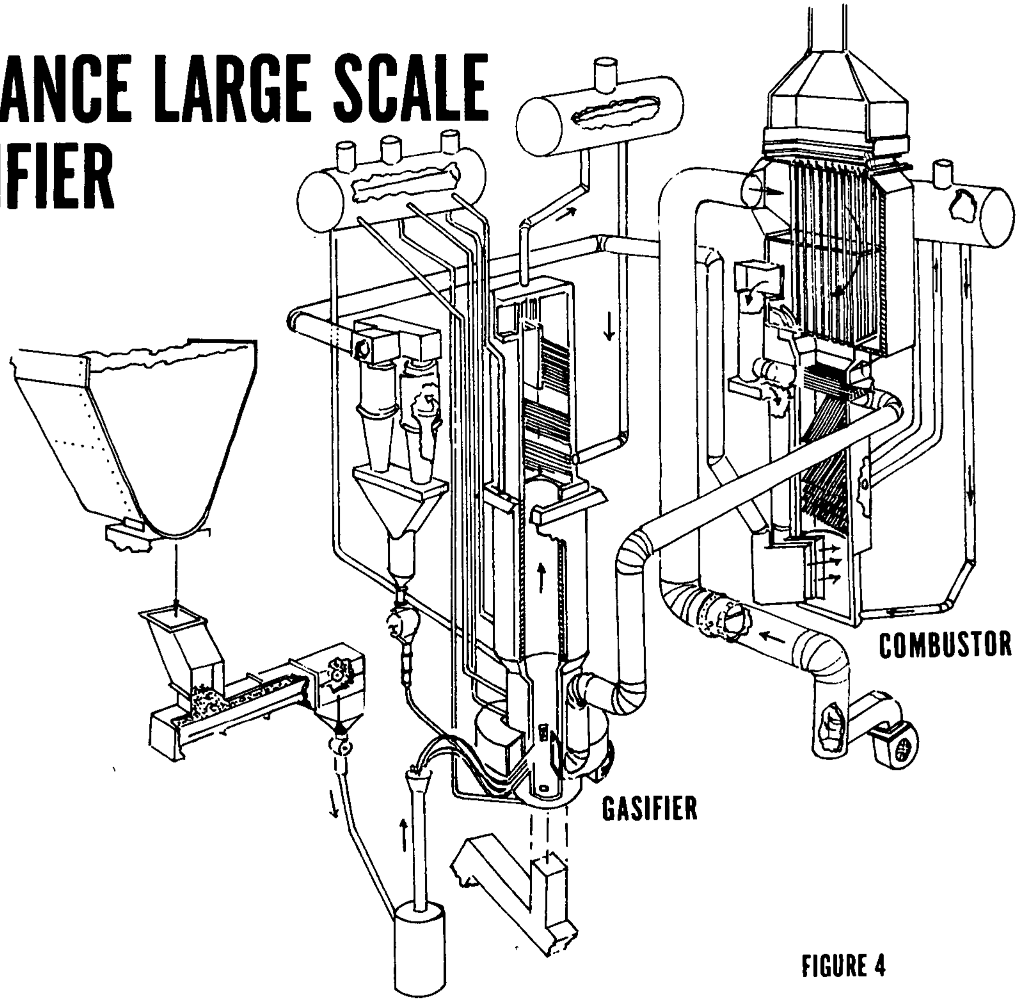


FIGURE 4

VERTICAL VORTEX GASIFIER

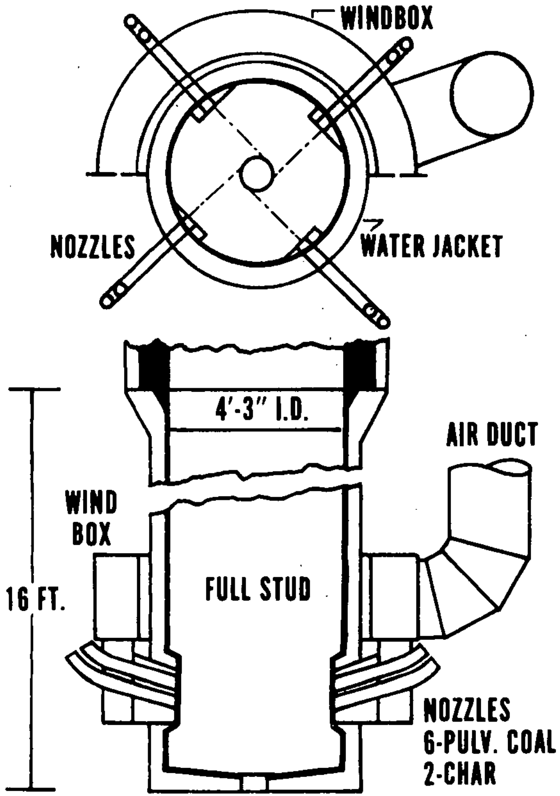


FIGURE 6

HORIZONTAL CYCLONE GASIFIER

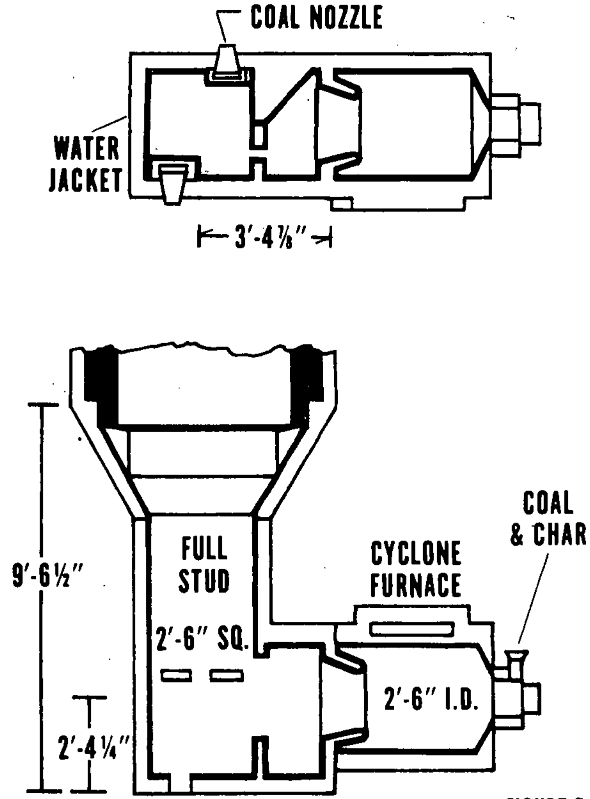


FIGURE 5

GAS CLEANING AND TURBINE GRID TEST

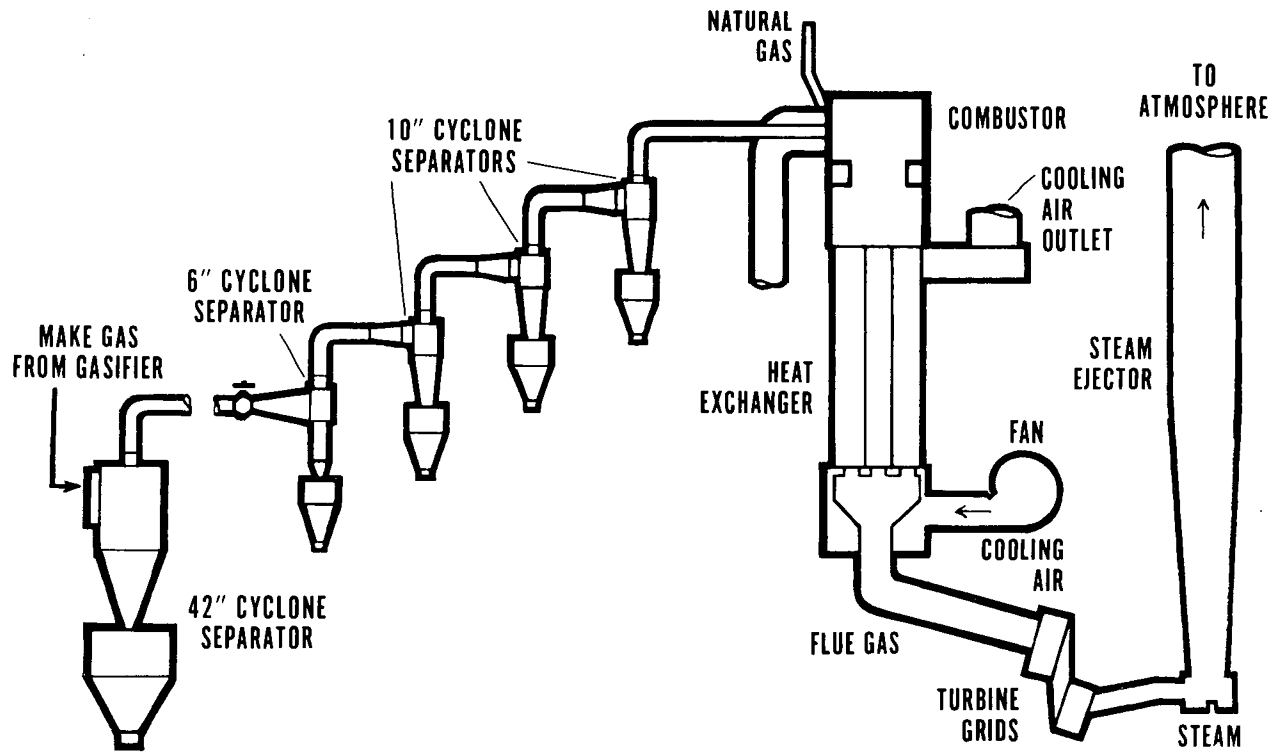


FIGURE 7

COMBINED STEAM-GAS TURBINE-CYCLE, WITH SUPERCHARGED GASIFIER AND BOILER

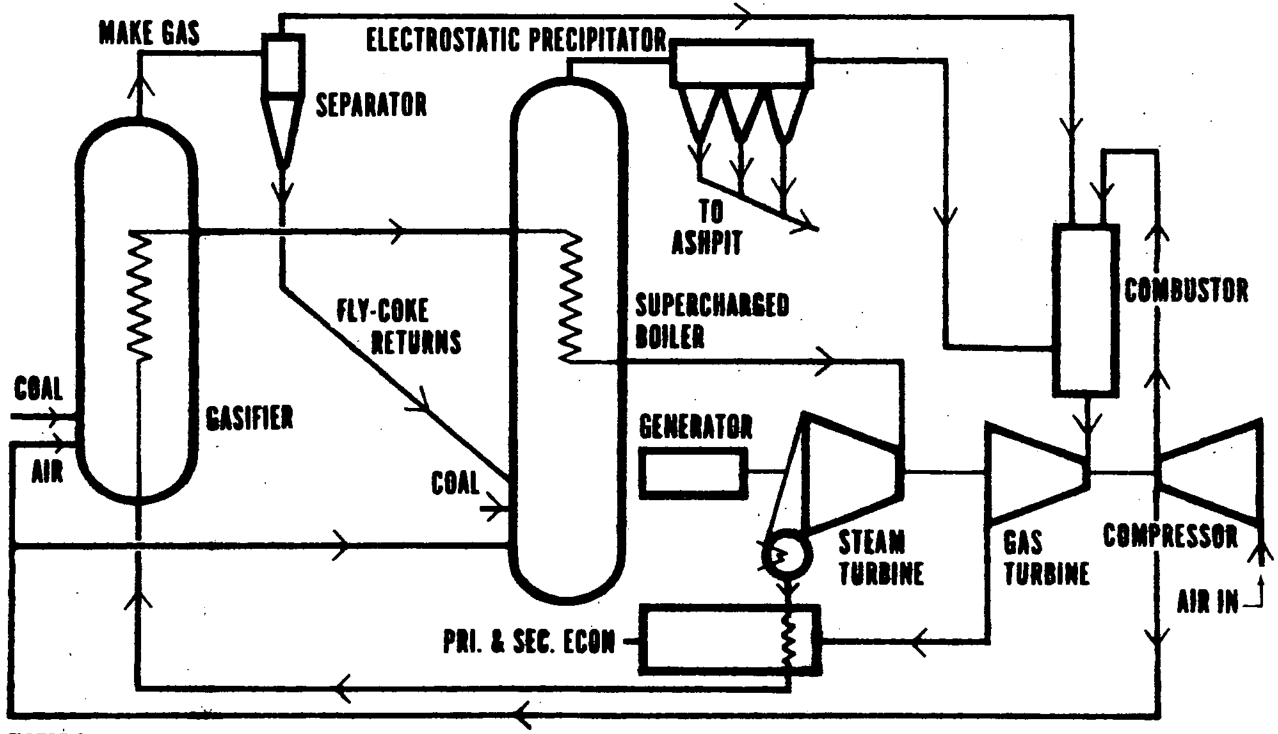
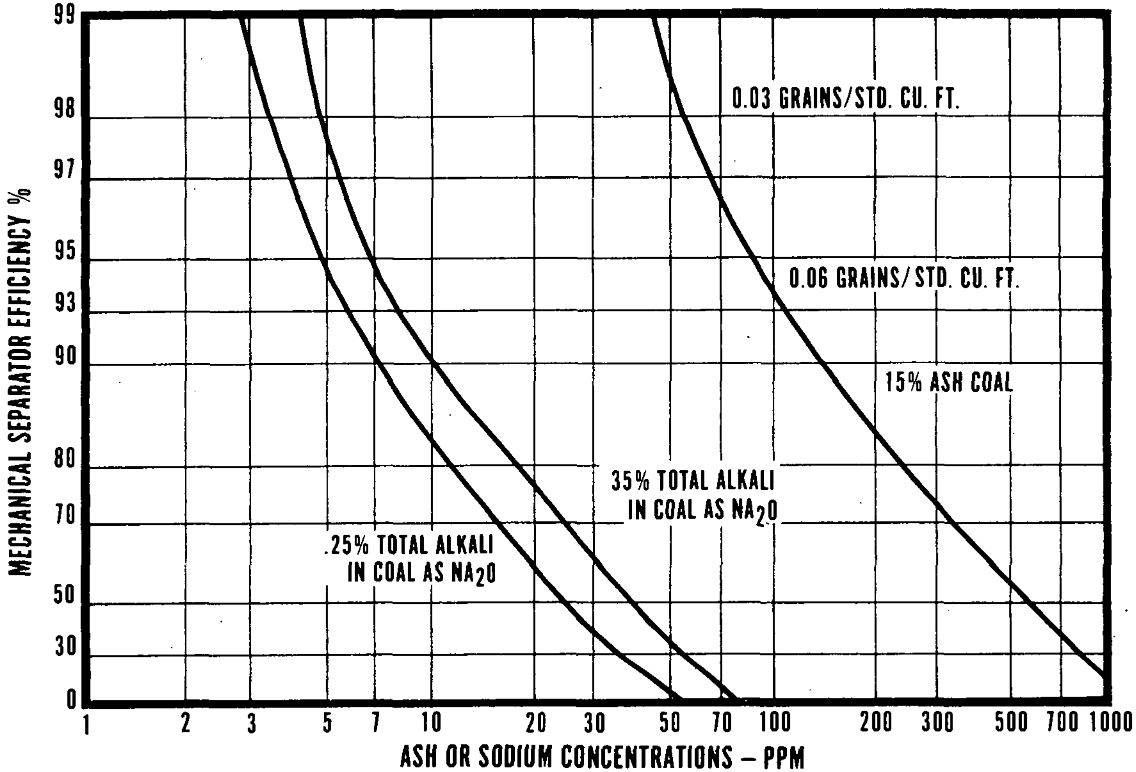


FIGURE 8

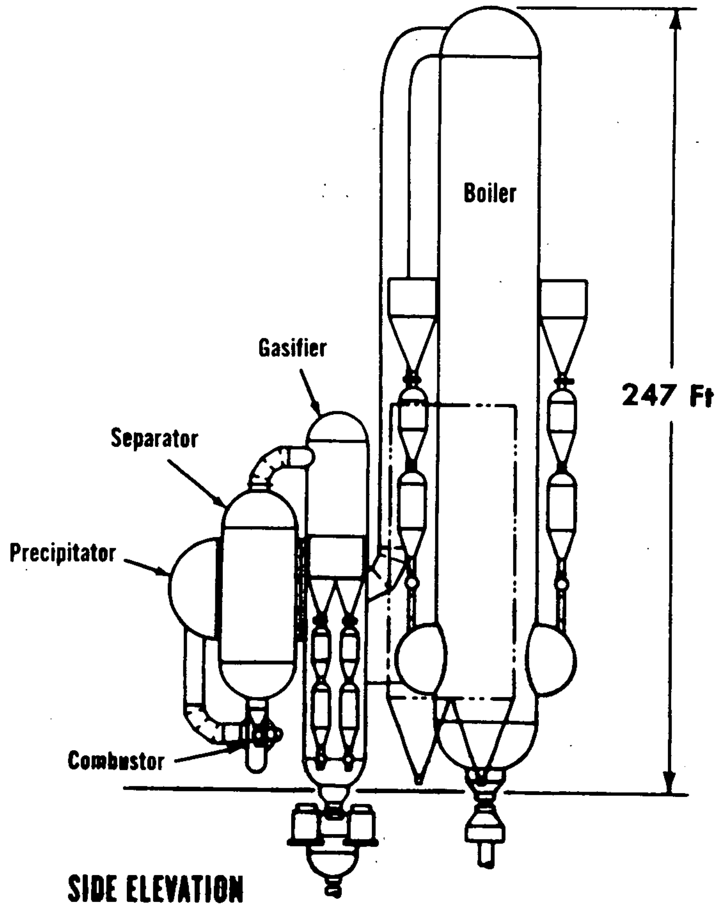
CONCENTRATIONS TO GAS TURBINE



ASSUMED CONDITIONS

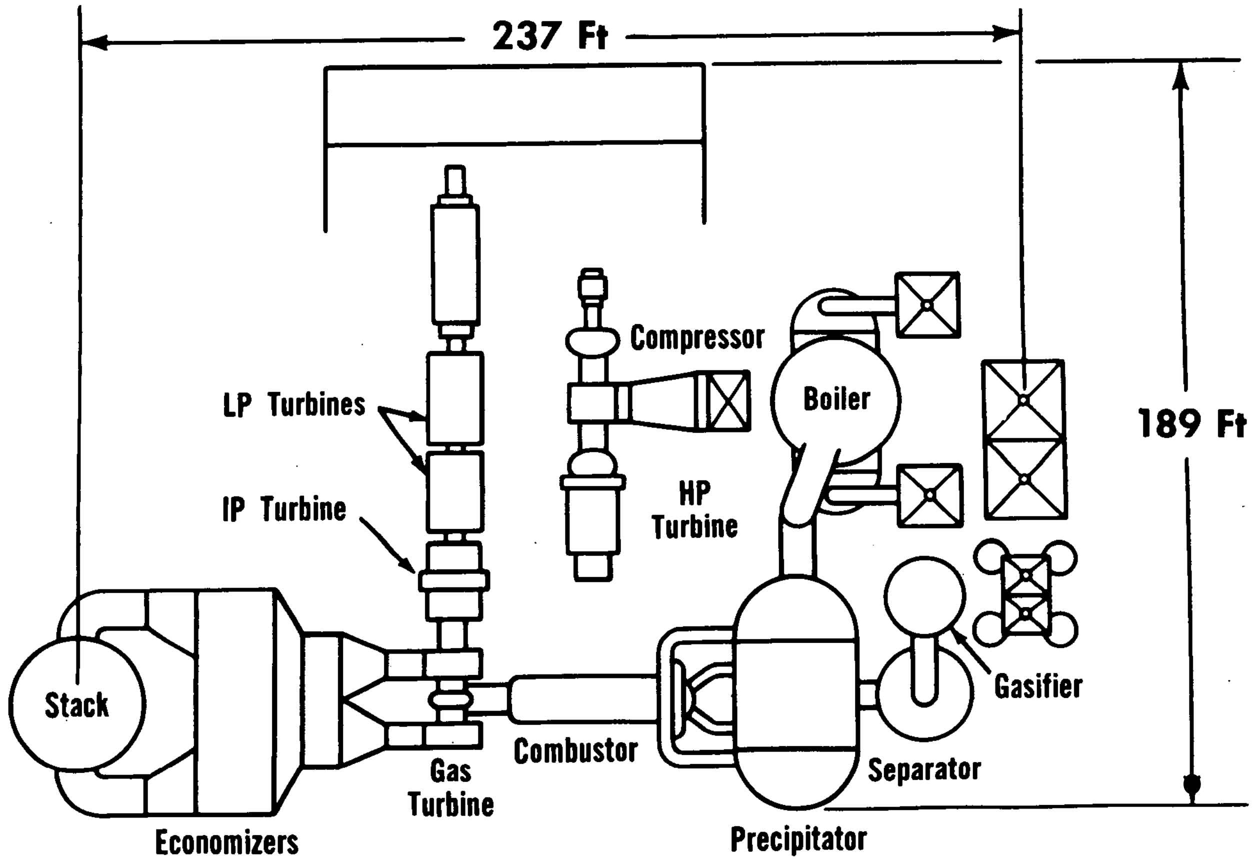
ELECTROSTATIC PRECIPITATOR EFF. 90%
GASIFIER ASH SLAGGING EFF. 80%
SUPERCHARGED BOILER ASH SLAGGING EFF. 85%
SUPERCHARGED BOILER & GASIFIER ALKALI SLAGGING EFF. 25%

FIGURE 9



450 MW STEAM-GAS TURBINE PLANT

FIGURE 10



Plan View

450 MW STEAM-GAS TURBINE PLANT

FIGURE 11

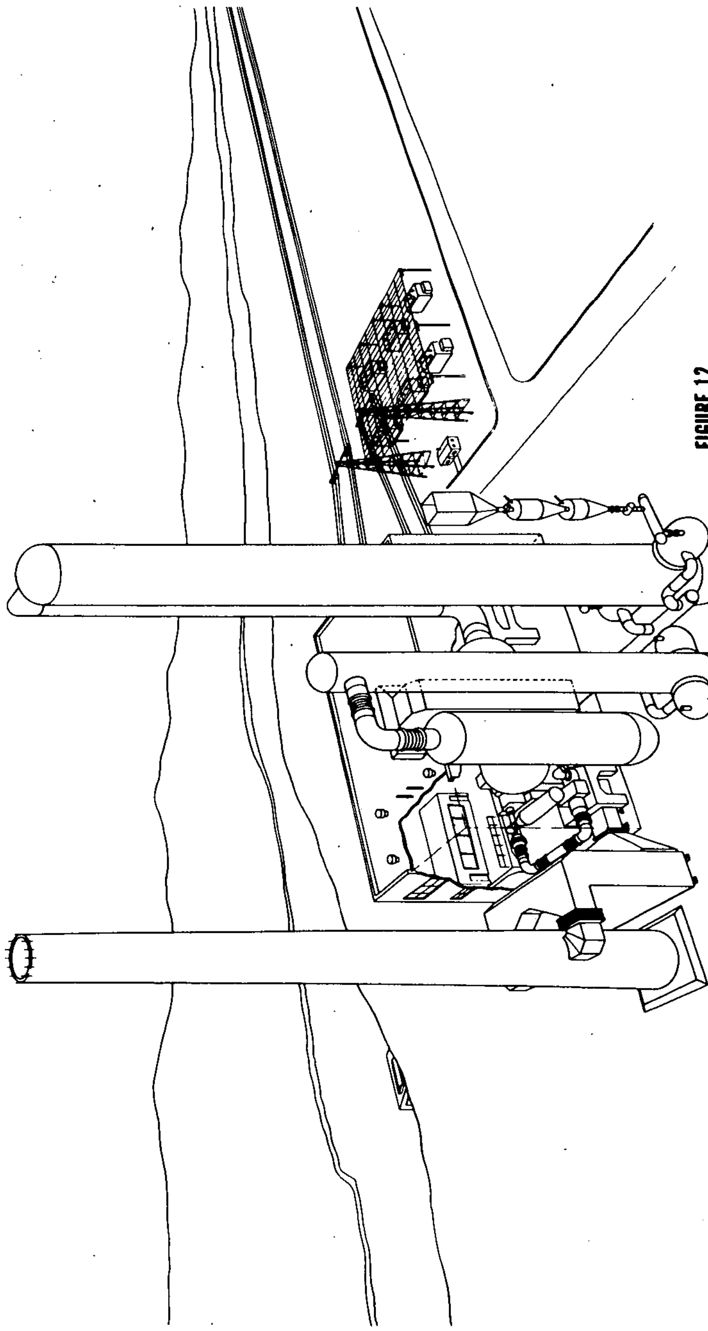


FIGURE 12

450 MW STEAM-GAS TURBINE PLANT

ADVANCED POWER CYCLE FOR AIR POLLUTION CONTROL

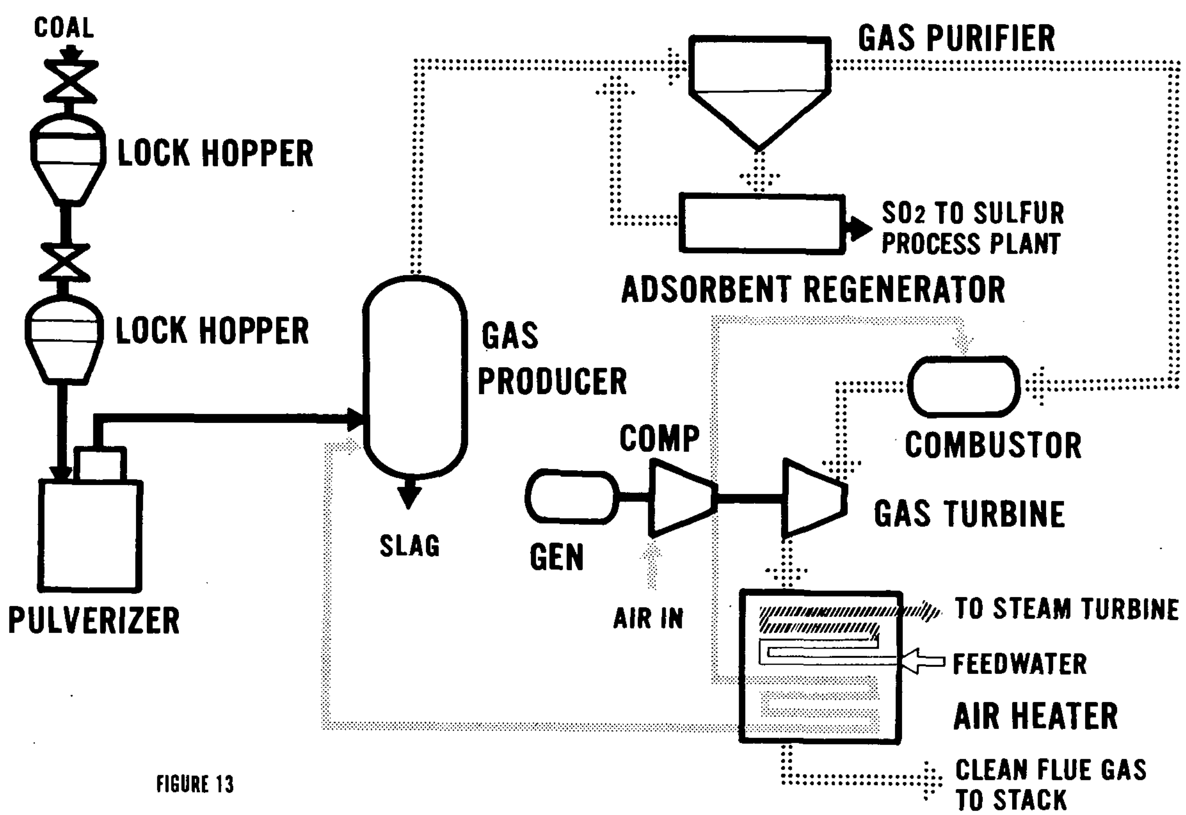


FIGURE 13